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The primary objective of this research work was to develop preliminary designs of aircraft wing/store configurations to achieve improved flutter performance in the transonic regime. In this research work, a methodology was developed to incorporate the nonlinearities associated with the wing and store in transonic regime into the multidisciplinary environment. Investigated the aeroelastic effects of the wing with and without the inclusion of store aerodynamics. The tip store configurations and underwing store configurations were analyzed independently. The results indicated that the inclusion of tip and underwing store aerodynamics does not have any significant impact on the flutter velocity in the transonic regime for these wing/store configurations. Mathematical optimization techniques were used for redesigning the wing structure. The research work addressed the need for higher fidelity aerodynamic analysis in preliminary design stages of aircraft design. Particularly, these findings are useful for store certification.

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Final Report

Computational Mechanics Approach for Multidisciplinary Nonlinear Sensitivity Analysis

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AFOSR Grant Number: F49620-01-1-0179
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Research Objectives

The primary objective of this research work was to develop preliminary designs of aircraft wing/store configurations in order to achieve improved flutter performance in the transonic regime. In this research work, a methodology was developed to incorporate the nonlinearities associated with the wing and store in the transonic regime into the multidisciplinary environment. However, combining a nonlinear aerodynamic analysis with optimization is computationally expensive and difficult task. Therefore, many parameters that were insignificant in the analyses needed to be identified and excluded. In order to identify the important parameters, the flutter sensitivity of given wing/store configurations were analyzed with respect to the store structural parameters.

Following were the tasks performed during the course of this research program to accomplish the above objectives:

1. Analyze the flutter sensitivity to store structural parameters in the transonic region.
   a) **Tip store: -** Location of store center of gravity (c.g.) with respect to aerodynamic chord and store mass.
   b) **Underwing store: -** Location of store c.g. with respect to aerodynamic chord, span and underwing clearance.
2. Understand the occurrence of store-induced Limit-Cycle Oscillation (LCO) and accurately predict its sensitivity to store structural parameters in a highly nonlinear design environment.
3. Investigate if store aerodynamics needs to be included in the modeling, while predicting the store-induced flutter behavior.
4. Identify the sensitive parameters affecting flutter and LCO and develop an optimization procedure to design a wing structure based on multidisciplinary performance constraints to delay their occurrence in the transonic regime.

Relevance to U.S. Air Force

The present work supplemented the ongoing research being performed at AFRL, WPAFB by investigating the effects of nonlinear phenomena taking place in flight vehicles carrying stores (missiles, launchers, fuel tanks, etc.). The research work was

divided into two phases. The first phase involved an investigation into the effect of varying store structural parameters on different wing/store configurations in the transonic region and provide additional information for future store certifications. The information obtained from this work helps in significantly reducing the number of extensive and expensive flight tests involved in store certification. It also helps in identifying the critical parameters that directly affect the store-induced flutter and LCO in the transonic region. By obtaining an increased understanding of flutter and LCO sensitivity to parameters, the behavior of such phenomena is easily predicted that results in reduced computational time and costs involved. The second phase involved the optimization of critical store structural parameters that help in delaying the occurrence of store-induced flutter of a fighter aircraft. The optimization of parameters during the design procedure increases the air vehicle life, performance and flight envelope.

Accomplishments/Findings

In this research work, tip store configurations and underwing store configurations were analyzed independently. The following were the findings of flutter sensitivity to various store structural parameters:

(i) **Location of store (tip and underwing) center of gravity with respect to aerodynamic chord**: The results indicate that the flutter velocity of the aircraft wing for both tip and underwing store cases increases, if the store center of gravity is moved forward of the elastic axis of the wing. But, the extent to which the store can be moved forward depends on the design constraints of store parameters and structural response.

(ii) **Tip store mass:** The flutter speed decreases with an increased store mass. It was also found that the occurrence of transonic dip tend to disappear for an increase in store mass. However, the decrease in flutter speed was very rapid for such stores. This indicates a decrease in the flight envelope of the aircraft.

(iii) **Location of underwing store along the span of the wing**: The results indicate that, as the underwing store is moved closer to the aerodynamic root chord, the flutter velocity increases, thereby indicating that the underwing stores can be placed near the fuselage in order to delay the occurrence of flutter.

(iv) **Underwing clearance (pylon length):** The results indicate that as the underwing clearance between the store and the lower skin of the wing increases, the flutter velocity decreases due to the structural deformations associated with the pylon. Even though, realistically, the pylon is stiff, these deformations are dominant over the aerodynamic interference effects between the store and pylon.

Also, studies were conducted to identify the onset of LCO for different configurations of the store (tip and underwing) and flight regimes (unmatched analysis). In the case of a tip store, the analysis was conducted for three different tip store mass values. It was found that the LCO onset velocity decreased sharply with the addition of the tip store mass. However, in case of an underwing store, there was no presence of LCO for the chosen configurations.

Furthermore, investigations on the effects of including tip and underwing store aerodynamics on the onset of flutter was conducted. The results indicated that the inclusion of tip and underwing store aerodynamics does not have any significant impact on the flutter velocity in the transonic regime for these wing/store configurations. Above findings helped in choosing the critical wing/store (tip and underwing) configurations for the optimization problem.

The second phase involved the optimization of both types of wing/store configurations (tip and underwing store), so as to delay the occurrence of store-induced flutter in the transonic regime. The implementation of optimization during the design procedure provides information that increases air vehicle mission performance, and flight envelope. During this phase, a study was conducted to find the significance of including the parameters of the ***Computational Aeroelasticity Program-Transonic Small Disturbance*** (CAP-TSD) into the optimization problem. This study was conducted by optimizing the structural parameters associated with the store using ***Automated STRuctural Optimization System*** (ASTROS), and then analyzing the flutter for this optimized structure using CAP-TSD. Furthermore, the percentage change in flutter speed between the ASTROS and CAP-TSD flutter results for initial and optimized wing/store designs for various constraints helped in understanding if it is essential to conduct

nonlinear analysis based optimization using CAP-TSD. In this study, store-induced flutter speed was increased by increasing the frequency separation between the first two flexible modes involved in flutter phenomena. Apart from the multiple frequency constraints, strength requirements were also considered. A flutter constraint was added to the stress and frequency constraints to study the impact of the flutter constraint. It was found that in the case of tip store wing configuration, the addition of the flutter constraint did not increase the flutter speed significantly in comparison to the optimized flutter speed obtained with just the frequency and stress constraints. However, in the case of the underwing store configuration, the flutter constraint was the active constraint, thereby enhancing the store-induced flutter speed in the transonic regime.

Usually, the nature or trend of flutter sensitivity with respect to the Mach number helps in the understanding of whether it is necessary to conduct nonlinear analysis-based optimization using CAP-TSD. The results indicated that it is not necessary to conduct a nonlinear analysis-based optimization in the preliminary design phase for improved flutter performance of the stores (tip and underwing) configuration in the transonic regime. In summary, this research work addressed the need for higher fidelity aerodynamic analysis in preliminary design stages of aircraft design. Particularly, these findings are useful for store certification.

Personnel Supported

The following graduate students were supported on this research program during the award period - Mr. Srinivasan Janardhan, and Mr. Chakradhar Byreddy.

Interactions/Transitions

The principal investigator and the graduate students interacted very closely with the Air Force Research Lab scientists at Wright-Patterson Air Force Base. This task compliments the research work being accomplished at AFRL by Dr. Phil Beran, Dr. Frank Eastep, Dr. N.S. Khot, Dr. Brian Sanders, and Mr. Larry Hutsell. Several meetings and technical exchanges took place during this reporting period.

Publications

1. Janardhan, S., Grandhi, R. V., Eastep, F., Sanders, B., "Parametric studies of transonic flutter and limit-cycle oscillation of an aircraft wing/tip store", *paper submitted to the AIAA Journal of Aircraft in January 2003.*
2. Byreddy, C., Grandhi, R.V., Beran, P., "Dynamic aeroelastic instabilities of an aircraft wing with an underwing store in transonic regime", *paper submitted to the Acta Astronautica Journal in May 2003.*
3. Janardhan, S., Grandhi, R. V., "Multidisciplinary optimization of an aircraft wing/tip store in the transonic regime", *paper submitted to the Journal of Engineering Optimization in July 2003.*
4. Byreddy, C., Grandhi, R.V., "Optimization of an aircraft wing with underwing store for improved flutter performance in transonic regime", *paper submitted to the Journal of Aerospace Engineering in July 2003.*

Meetings, Conferences and Symposium Presentations

The principal investigator presented the research work at the AFOSR annual meeting at Washington D.C. in September 2002. The graduate students have presented their research at the following conferences and symposiums:

1. Janardhan, S., Byreddy, C., Grandhi, R., Eastep, F., Sanders, B., "Sensitivity of flutter and Limit Cycle Oscillation of an aircraft wing with multiple store configurations", paper submitted to AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Years, Dayton, Ohio, 14 -17 July 2003.
2. Janardhan, S., Grandhi, R. V., Eastep, F., Sanders, B., "Design studies of transonic flutter and limit-cycle oscillation of an aircraft wing/tip store", paper presented at *44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference,* April 7-10, 2003, Norfolk, Virginia, AIAA-2003-1944.

3. Janardhan, S., Grandhi, R.V., Eastep, F.E., Sanders, B., "Transonic unsteady aeroelastic behavior of an aircraft wing/tip store", *Presented at 28th Annual Dayton-Cincinnati Aerospace Sciences Symposium, March 4, 2003.*
4. Byreddy, C., Grandhi, R.V., "Dynamic aeroelastic instabilities of an aircraft wing with an underwing store in transonic regime", *Presented at 28th Annual Dayton-Cincinnati Aerospace Sciences Symposium, March 4, 2003.*

Patent Disclosures

None

Honors/Awards

Honor/Award Recipient: Ramana V. Grandhi, ASME Fellow

Honor/Award: Distinguished Professor for Research (1996 - 2006),

University Professor (1998 – 2003).

Awarding Organization: Wright State University, Dayton, Ohio